Herschel MESS observations of cool dust and molecules in Galactic supernova remnants

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and

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Motivation: the origin of the dust in galaxies

Up until the late-90's the standard picture was that steady mass loss from evolved AGB stars was the primary source for the refractory dust grains found in the ISM (e.g. silicates and amorphous carbon).

From 1998 onwards the submm detection of large quantities of dust in high-z galaxies, beginning with SCUBA, began to force a change to this picture.

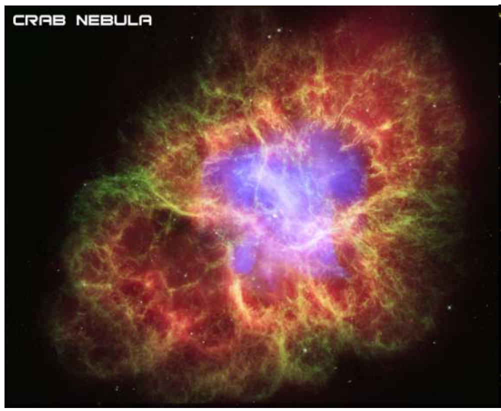
From dust nucleation modelling, Kozasa et al. (1991), Todini & Ferrara (2001) and subsequent authors have predicted that 0.1--1.0 Msun of dust could condense in the ejecta of of a typical high-z CCSN. Dust evolution models have estimated that at least 0.1 Msun of dust per SN is needed if the dust content of galaxies is to be influenced (without allowing for any dust destruction by shocks).

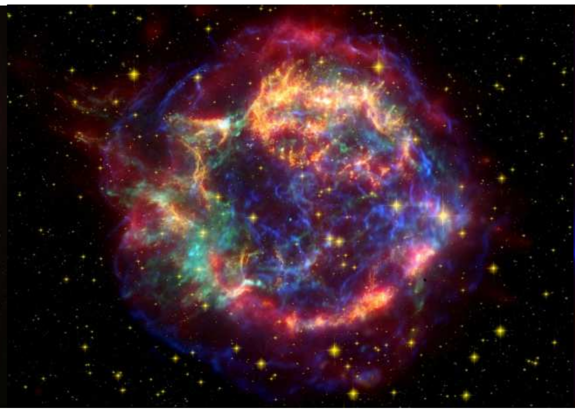
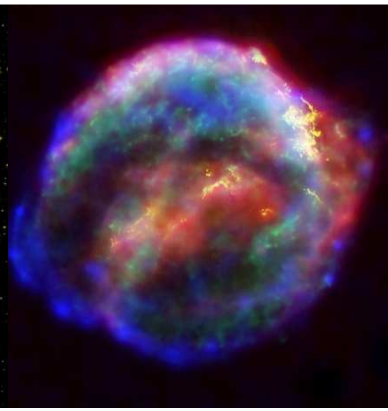
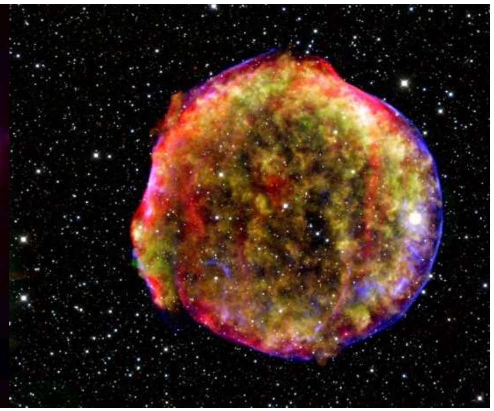
Herschel MESS SNR programme

Targets: 5 young Galactic supernova remnants; 35hrs GT

1680	IIb		(Cas A)
1604	Ia		(Kepler)
1572	Ia		(Tycho)
1181	II	(pulsar)	(3C58)
1054	II	(pulsar)	(Crab)

Young, nearby: swept-up ISM mass should be low



Herschel MESS SNR programme

PACS 70, 100, 160 μm imaging
SPIRE 250, 350, 500 μm imaging
(all five SNRs)

PACS 55-205 μm spectroscopy
(Cas A, Kepler, Tycho, Crab)

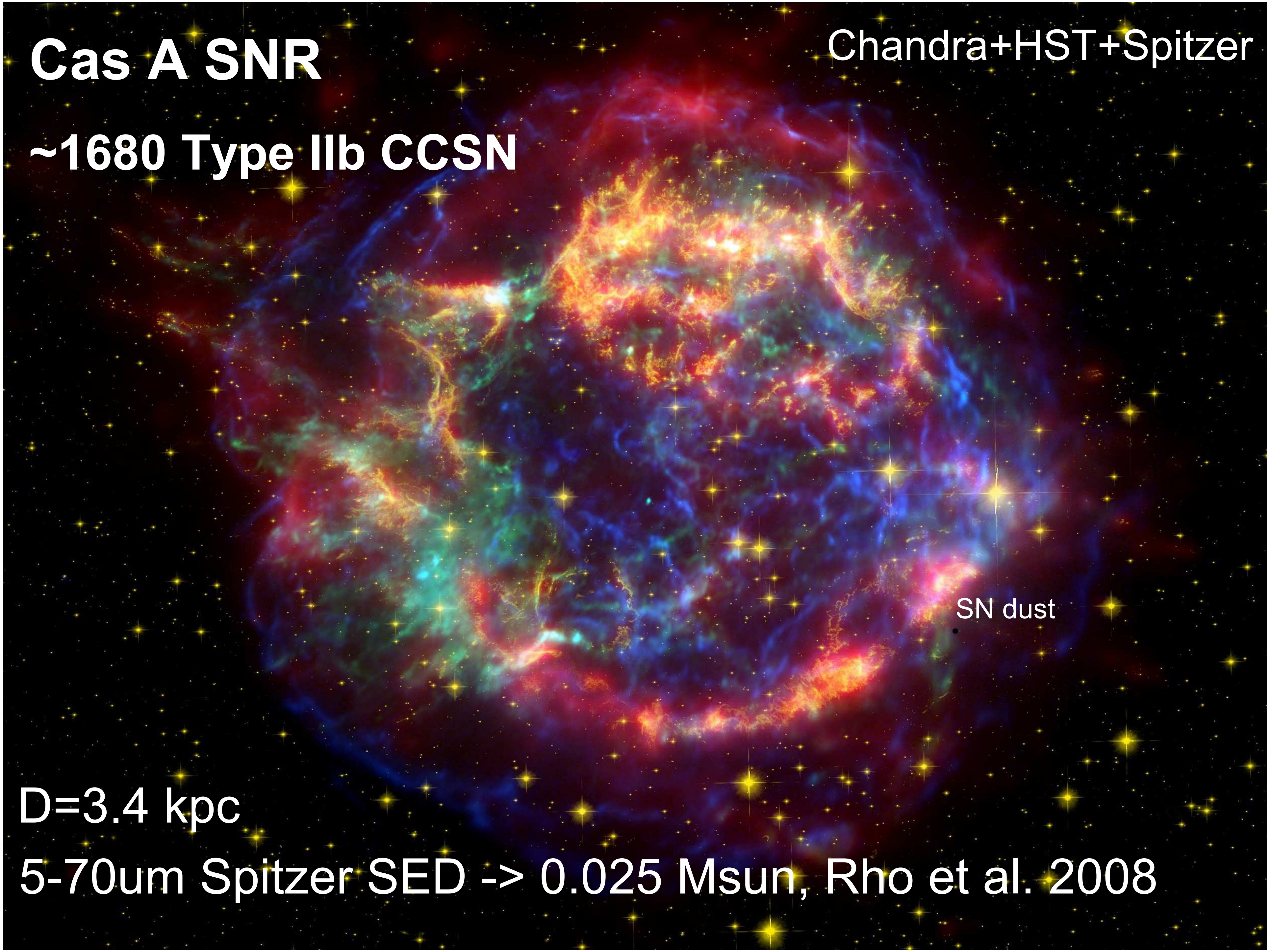
SPIRE FTS 195-670 μm spectroscopy
(Cas A, Crab, Tycho)

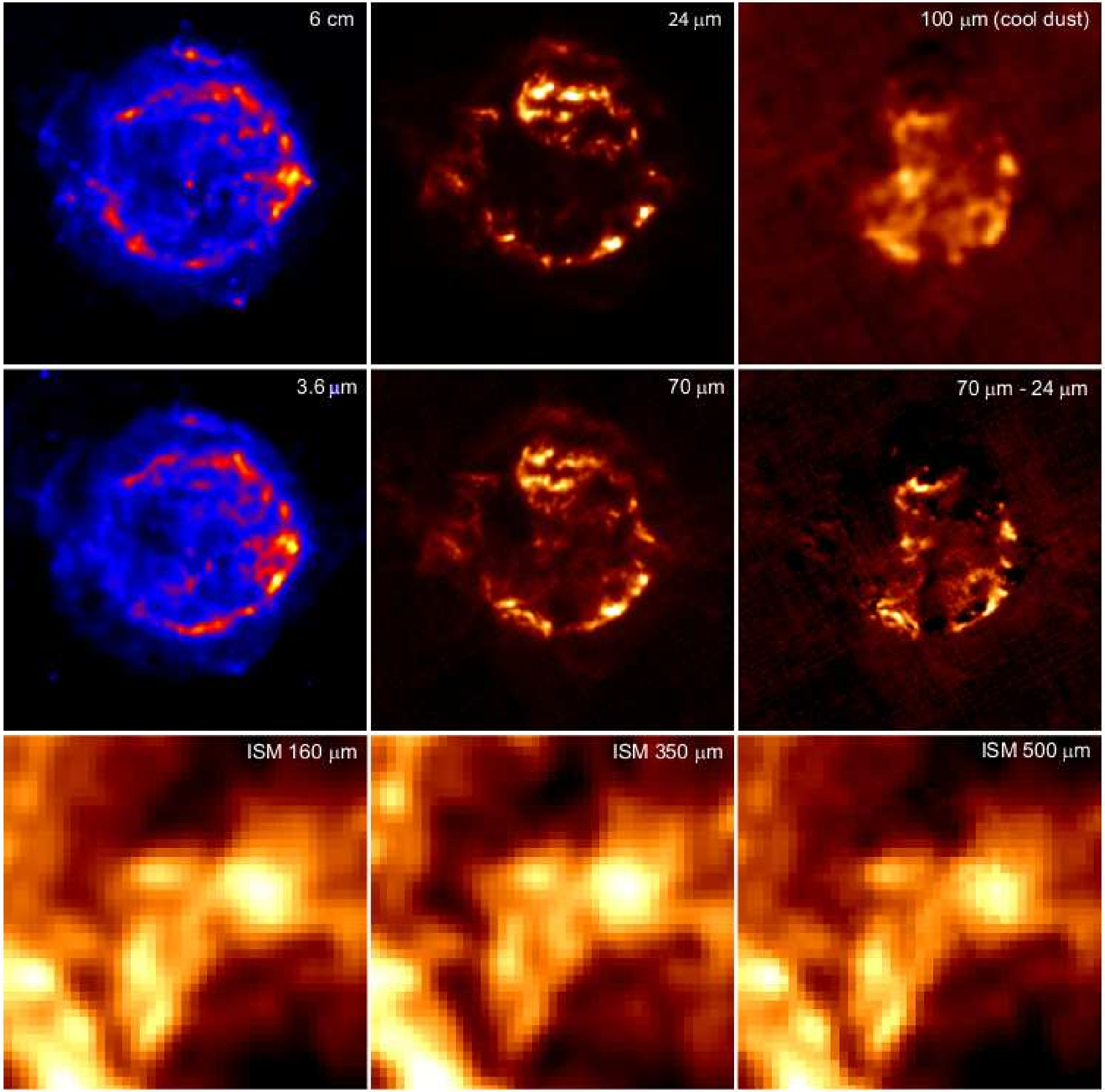
Science goals:

SNR dust content

Separation SNR / CSM / ISM dust

Gas diagnostics and kinematics


Cas A SNR
Chandra+HST+Spitzer
~1680 Type IIb CCSN
SN dust
D=3.4 kpc
5-70um Spitzer SED -> 0.025 Msun, Rho et al. 2008



Cas A

near-IR/far-IR/radio

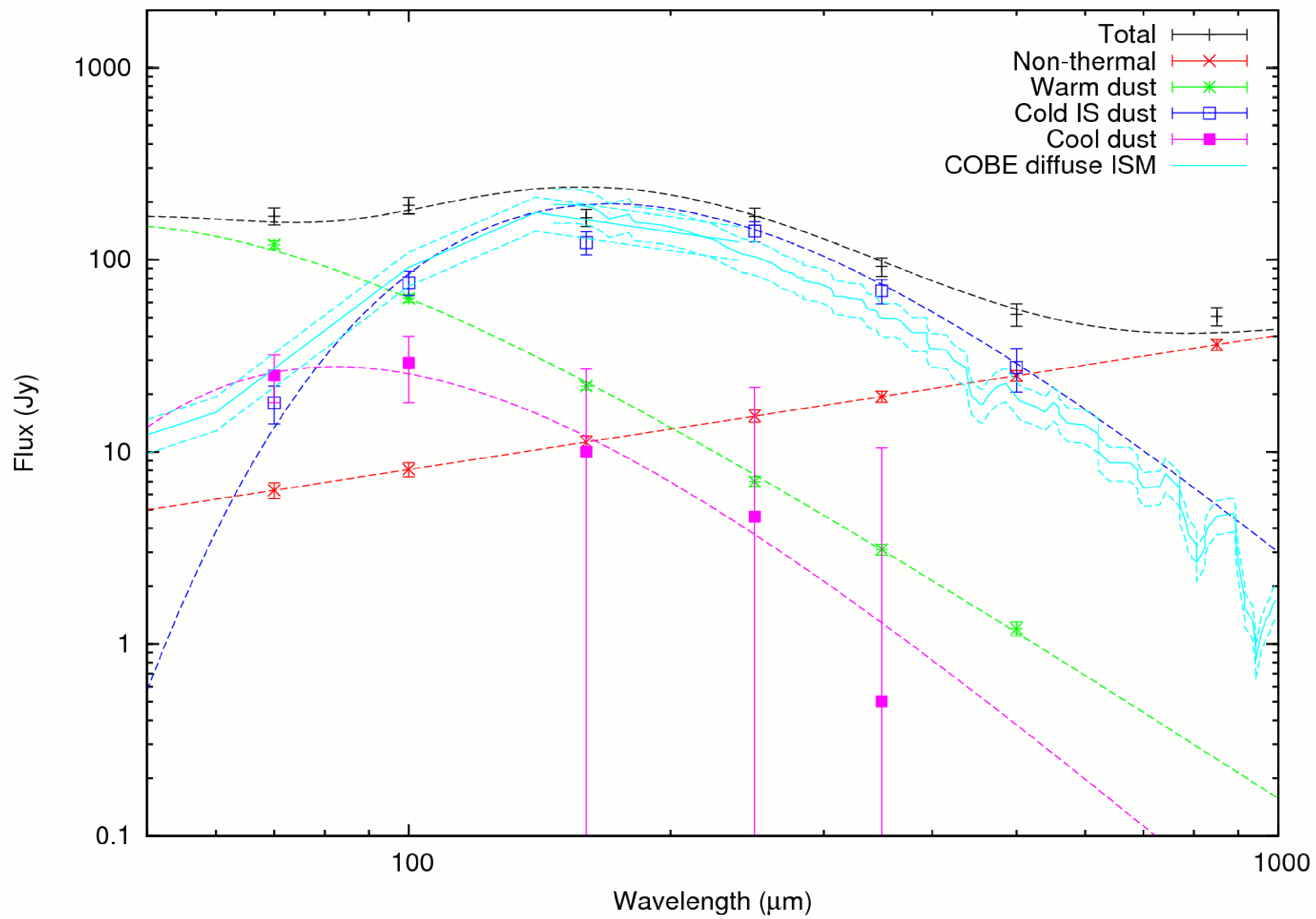
Barlow et al. (2010)

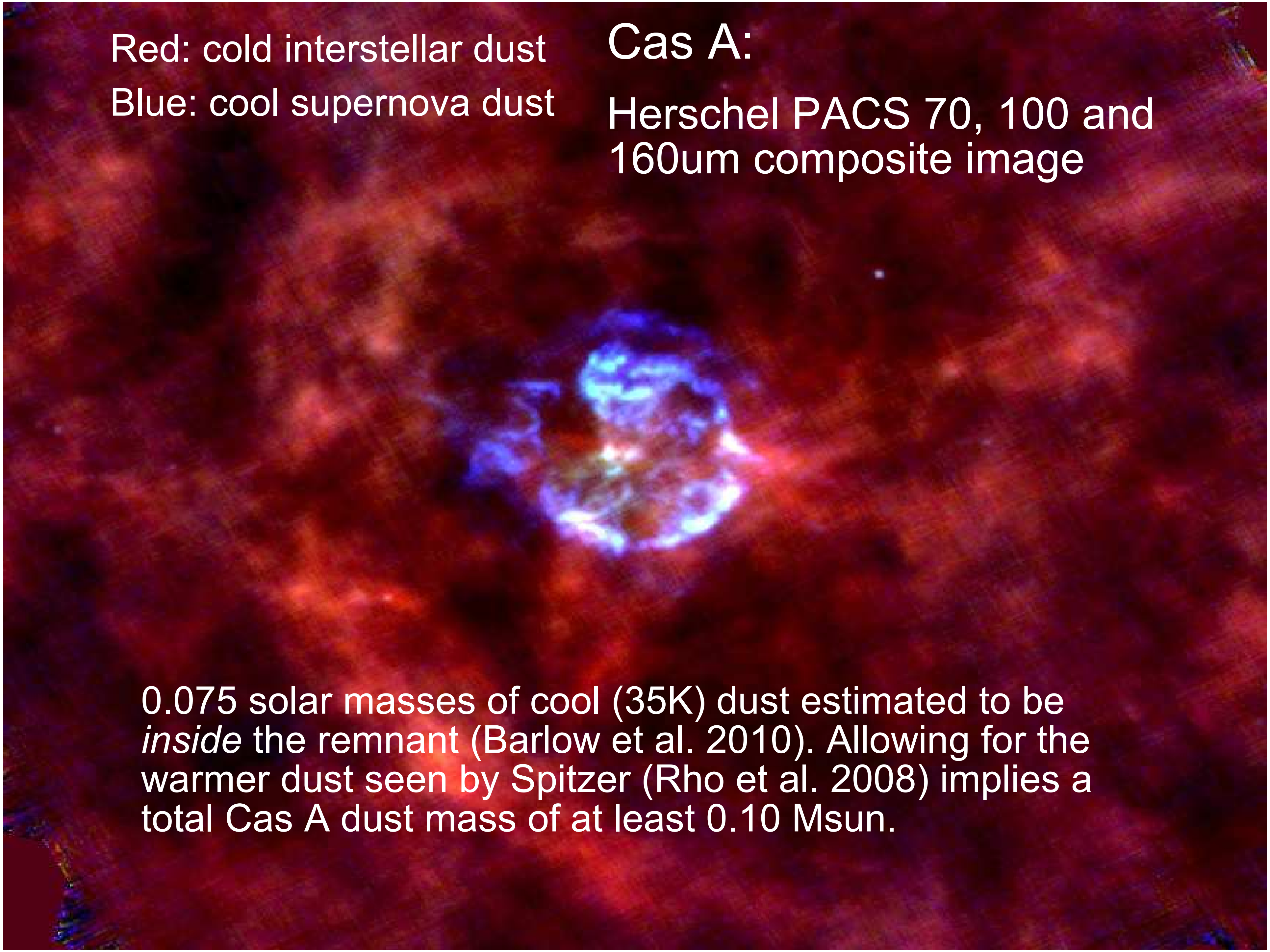
For this O-rich SNR, silicates were used to fit the dust SED

Cas A: 50-1000um SED

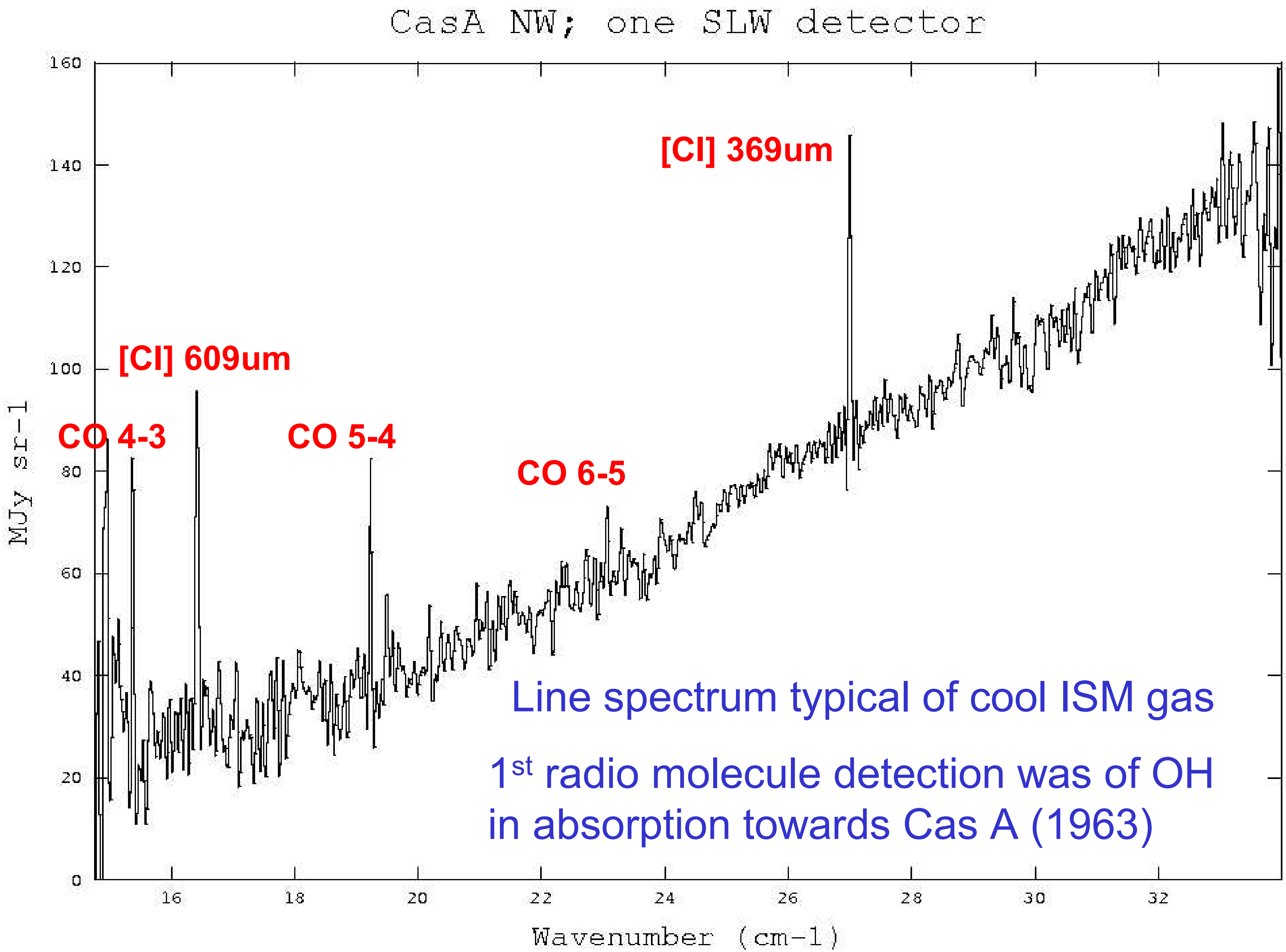
After subtraction of extrapolated non-thermal and warm dust components, the ISM cold dust SED from several points outside Cas A was normalised to 160um and subtracted, to yield a `cool' (~35K) Cas A silicate dust component.

The dominance of the cold ISM component means that a colder, more massive, dust component in Cas A could still be hidden.



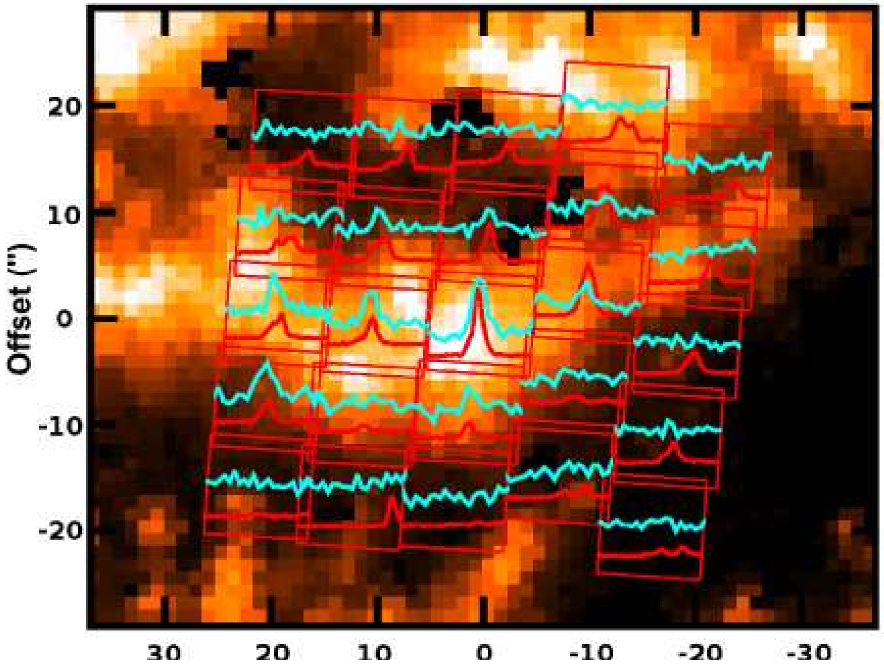

Red: cold interstellar dust
Blue: cool supernova dust
Cas A:
Herschel PACS 70, 100 and 160um composite image
0.075 solar masses of cool (35K) dust estimated to be *inside* the remnant (Barlow et al. 2010). Allowing for the warmer dust seen by Spitzer (Rho et al. 2008) implies a total Cas A dust mass of at least 0.10 Msun.

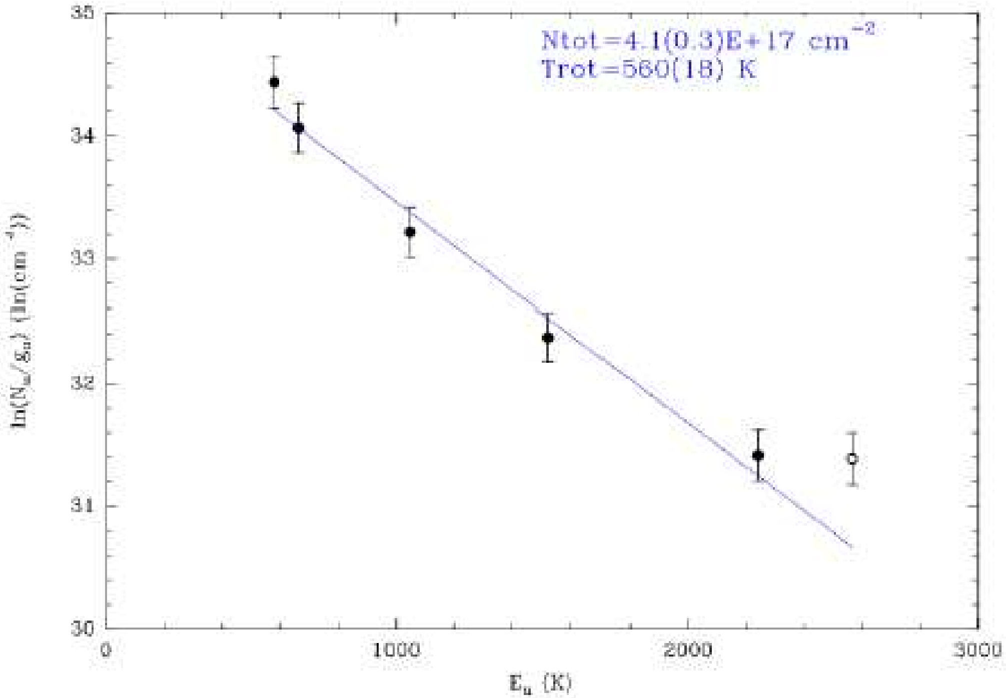
SPIRE FTS spectrum (one position)

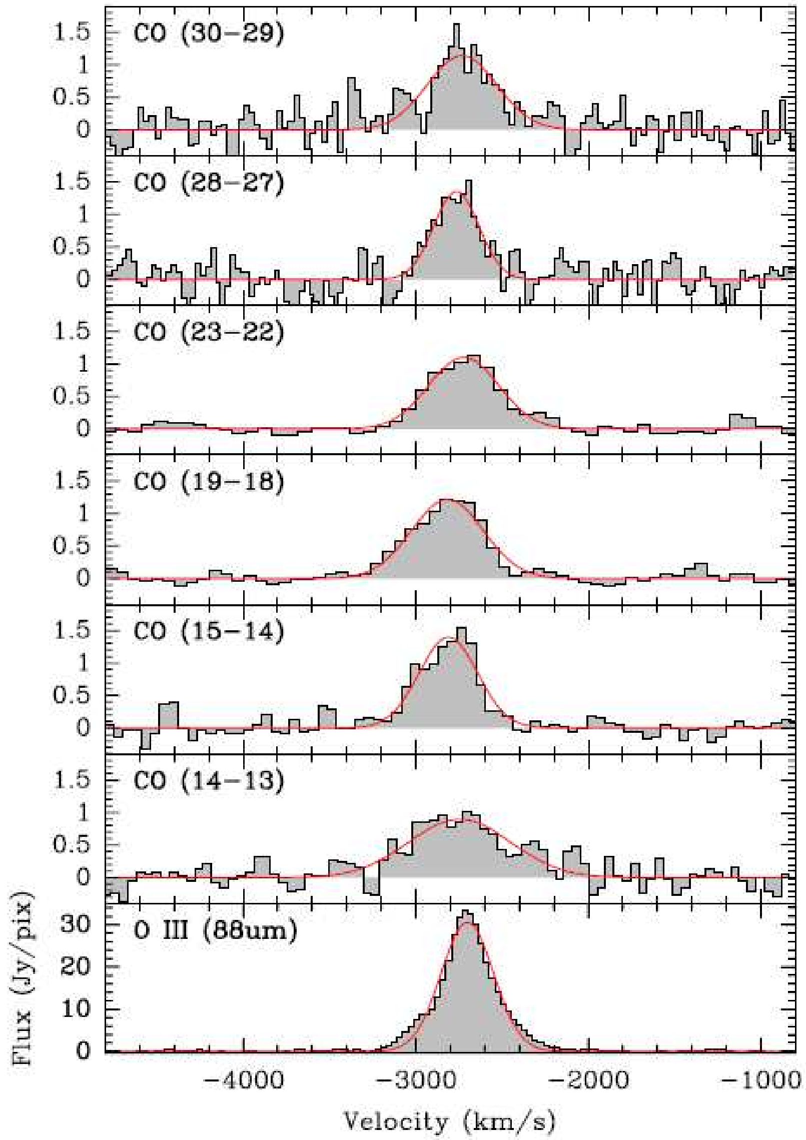


Line spectrum typical of cool ISM gas

1st radio molecule detection was of OH in absorption towards Cas A (1963)

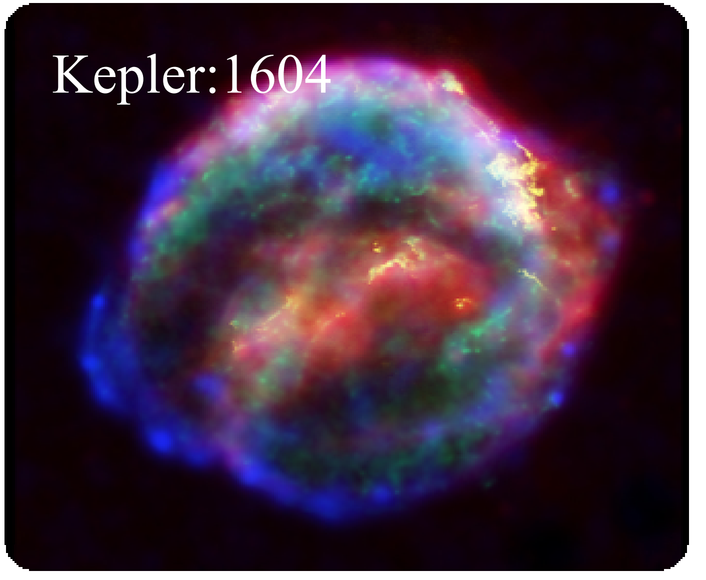


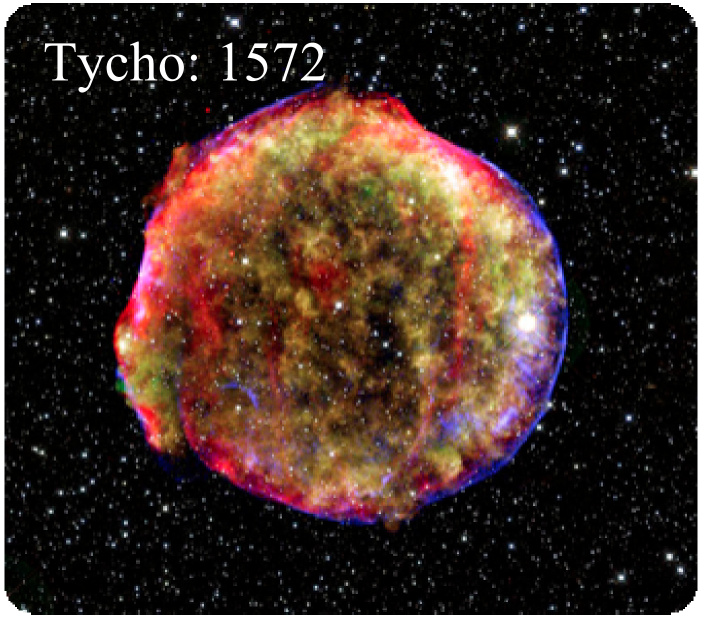




non-MESS OT PACS spectra of broad CO lines in Cas A (400-2000 K gas): Wallstrom et al. (A&A, 558, L2, 2013)

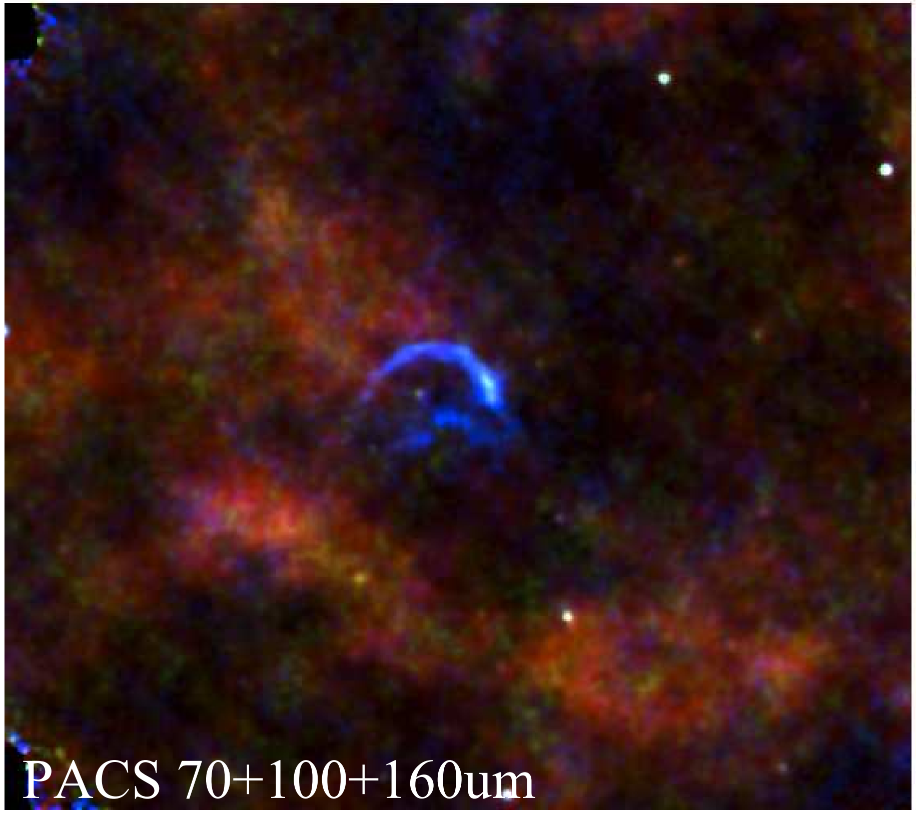
Type Ia supernova remnants

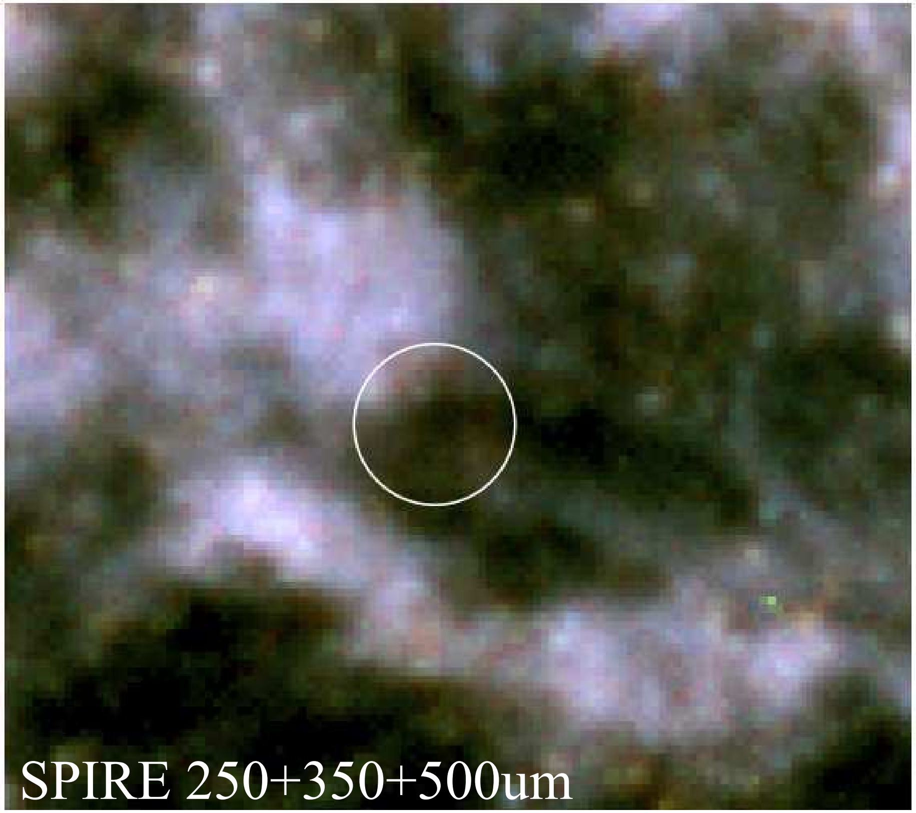




Kepler's supernova remnant

Gomez et al. (2012a)





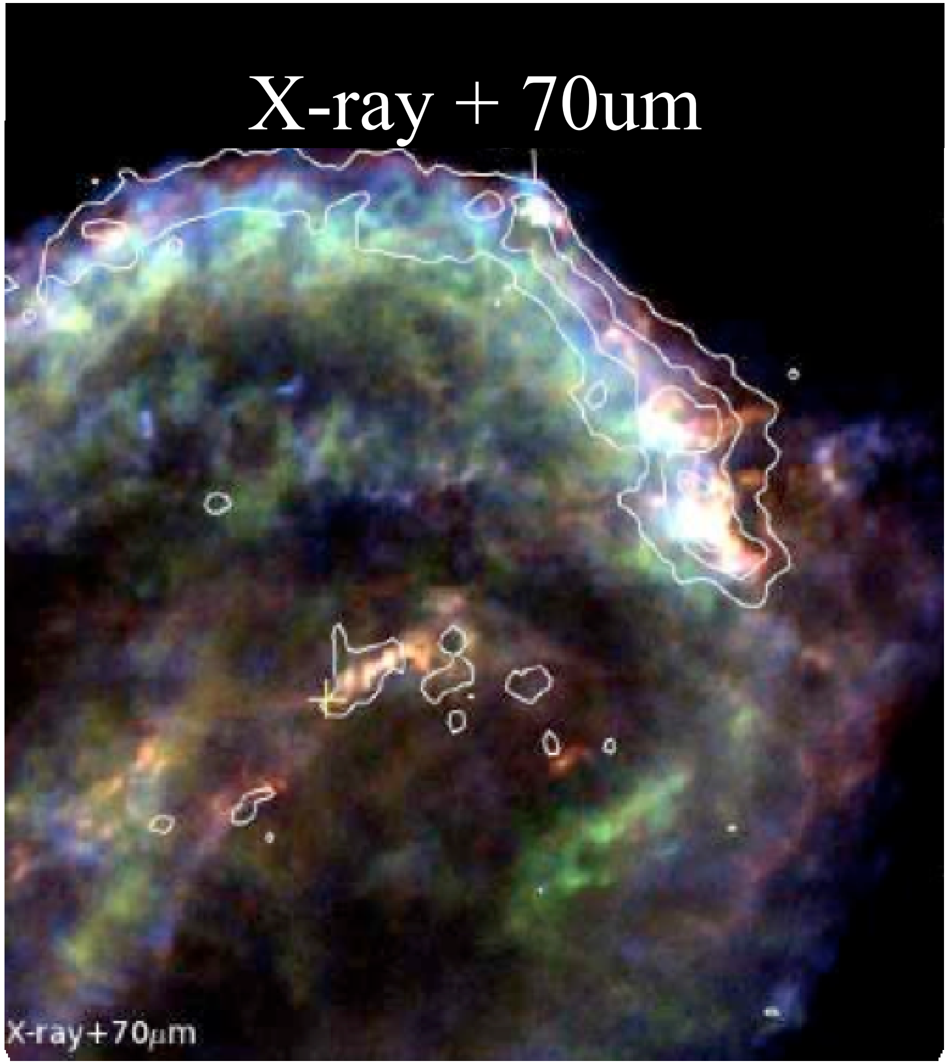
T=82+-5 K
Md ~ $3x10^{-3}$ Msun
for D = 4.0 kpc

T=20K
Md = 2.1 Msun (but interstellar dust)

No cold dust inside the remnant

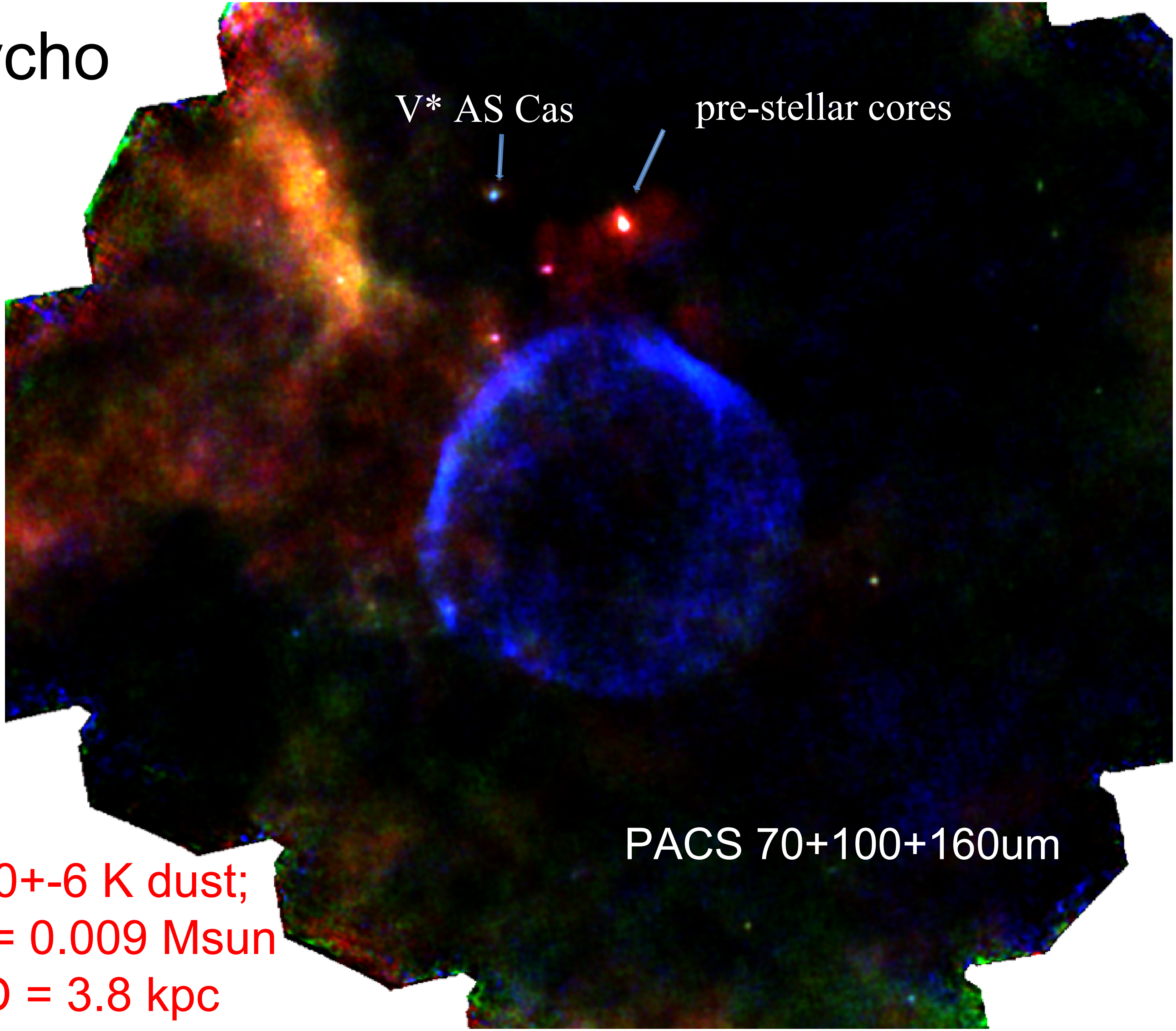
Gomez et al. (2012a)

The 80K dust at the edge is spatially coincident with soft X-ray and Hα emission that has been inferred to be swept-up CSM material.



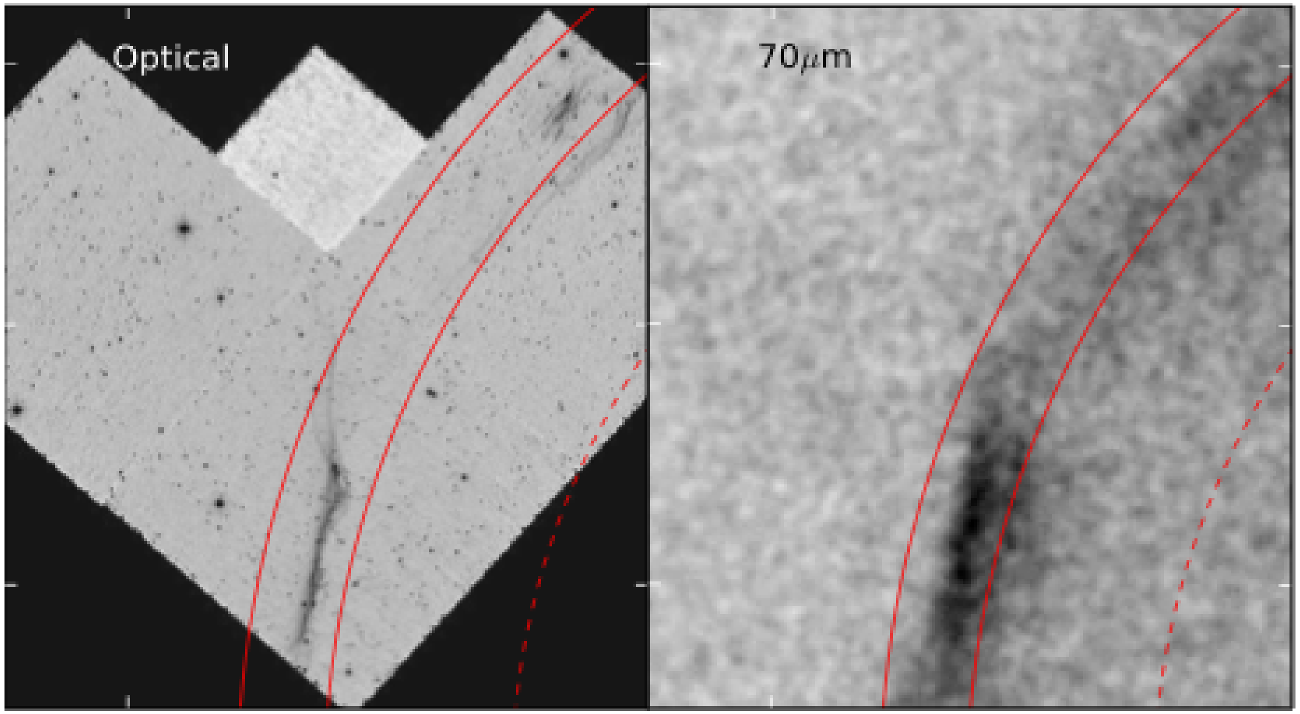
Kepler's remnant

Tycho



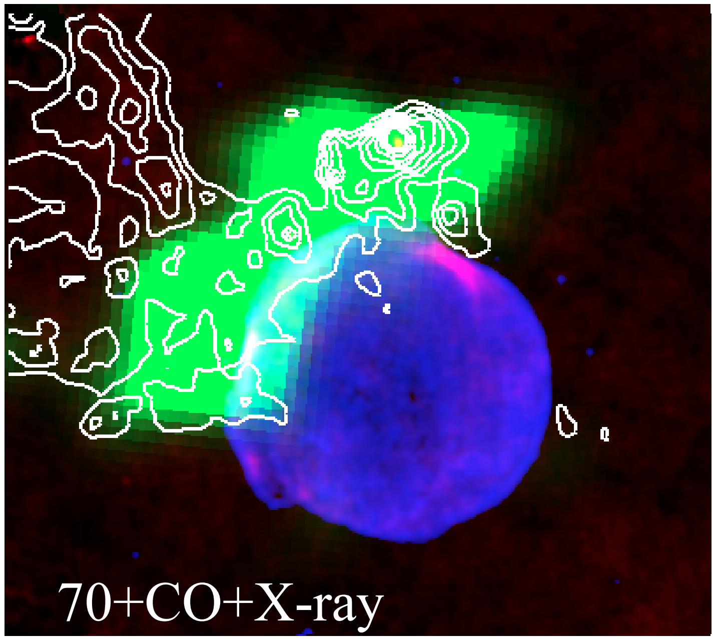
T=90+-6 K dust;
Md = 0.009 Msun
for D = 3.8 kpc

We see hot dust where the shock front meets surrounding gas



Tycho's remnant

No cold dust inside the remnant – the warm dust at the edge is consistent with swept-up ISM dust.



Gomez et al. 2012a

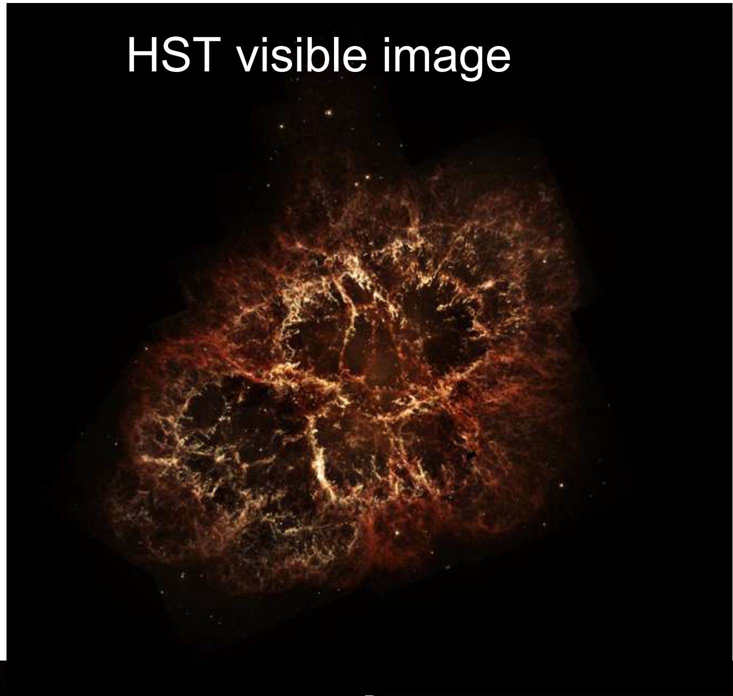
Type Ia supernovae are believed to provide most of the iron found in galaxies like the Milky Way; about 0.6 Msun of Fe per Type Ia.

The absence of dust particles inside Tycho and Kepler implies that their iron atoms must be in the gas-phase.

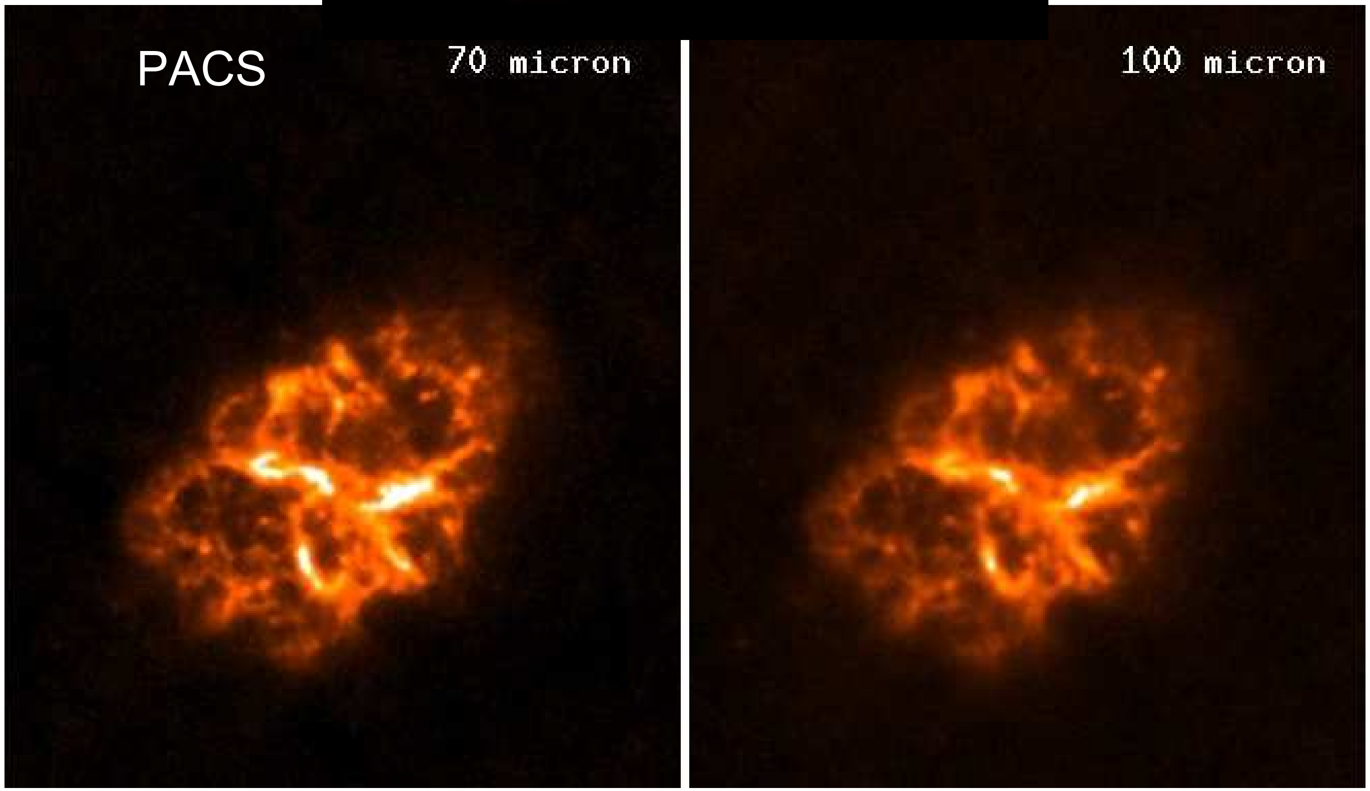
Yet in the diffuse ISM, gas-phase Fe has depletion factors of 10-100, with the missing atoms presumed to be locked up in dust grains

The Crab Nebula: the remnant of a Type II CCSN

D = 2 kpc



In the Galactic anti-centre direction, so interstellar dust emission is relatively low.



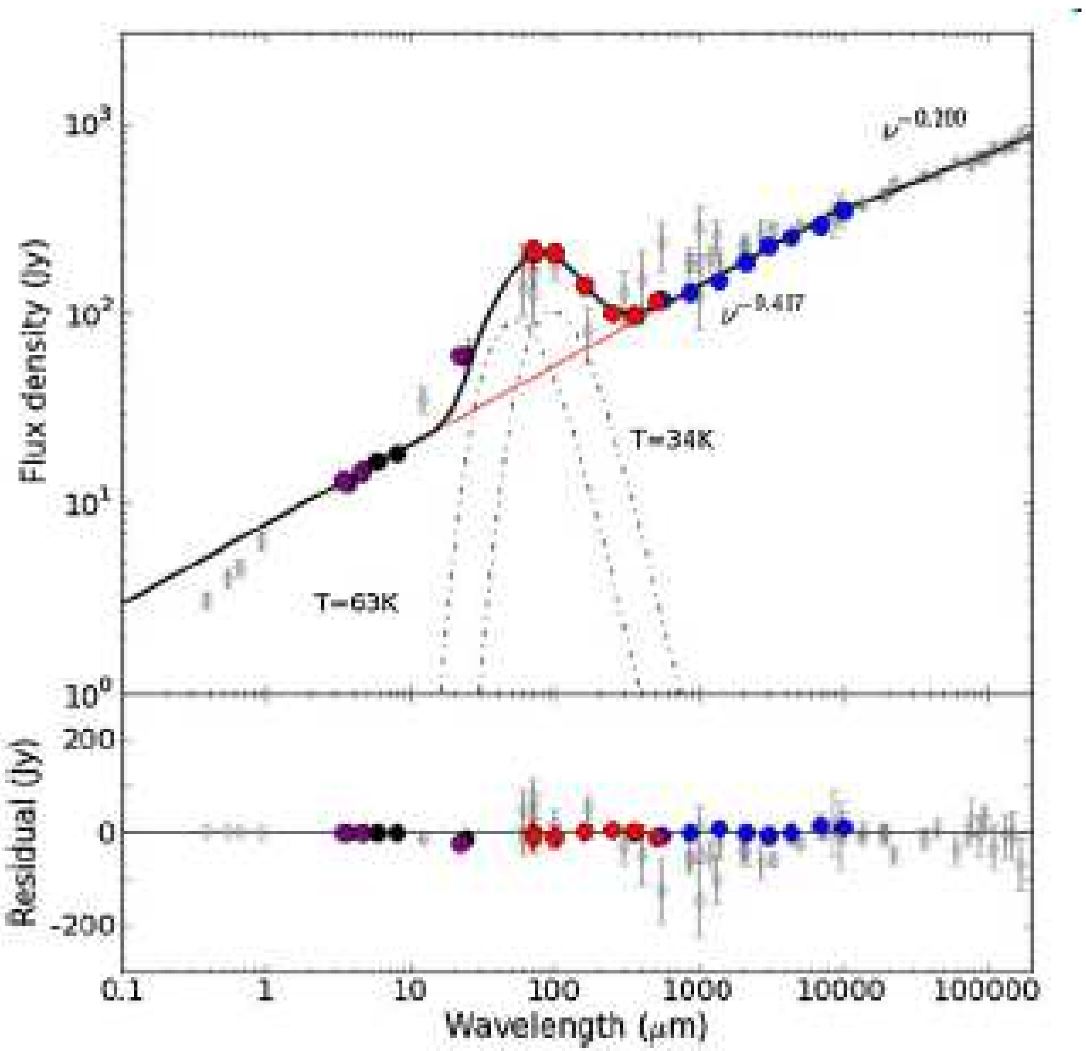
H. Gomez et al., *`A cool dust factory in the Crab Nebula', ApJ, 760, 96, 2012*

The blue points, from Planck, together with the SPIRE 350um and 500um points (red) and the Spitzer IRAC points (black), define the synchrotron component.

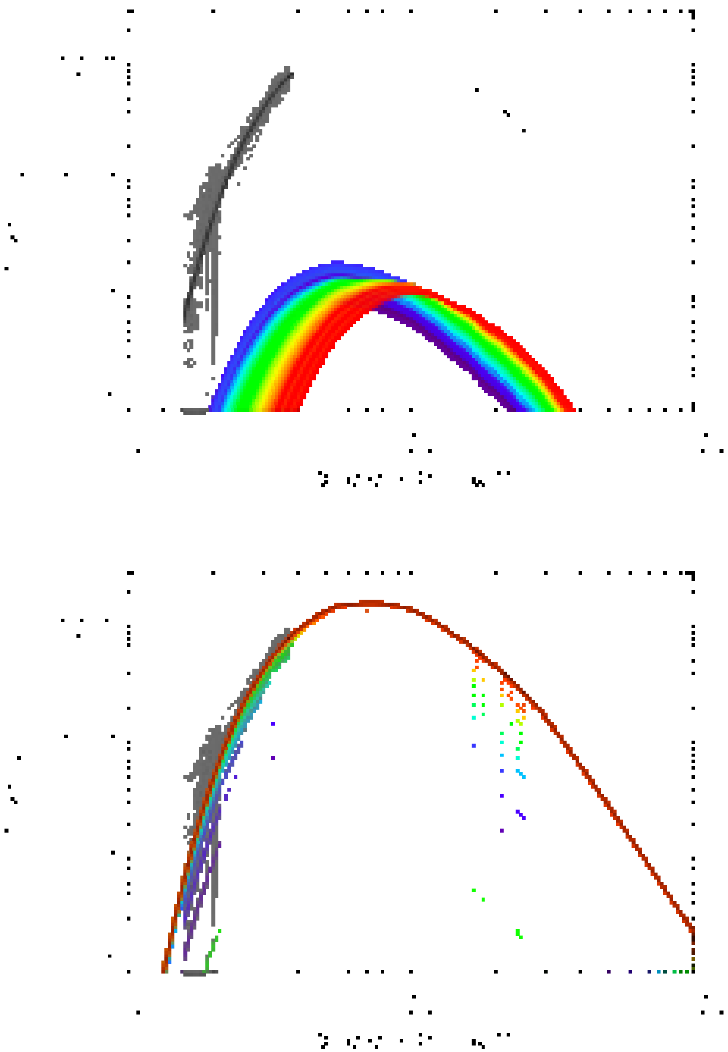
The dust component is defined by the Spitzer 24um and the Herschel 70, 100, 160 and 250um fluxes (red).

2-component modified BB fit:

Mdust = 0.11 Msun (carbon)
or 0.24 Msun (silicates)

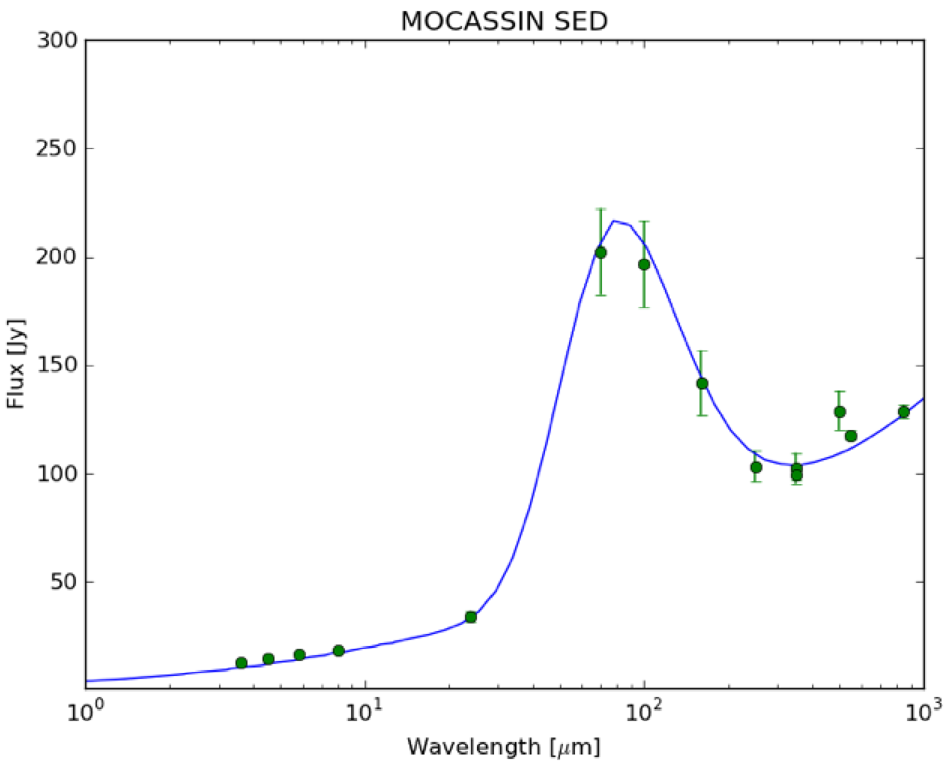


An Alternate View:
Temim and Dwek 2013, ApJ 774, 8



- Fitted a grain size/temperature distribution to the Herschel data
- Central point source adopted for RT
- 0.02-0.13 Mo of dust (all at the same nebular radius), with a power-law size distribution having α ~ 3.5 and a grain size range of 0.001-1.0 μm

(P.J. Owen, Wednesday 9b session)
Moccasin ionized gas+dust RT results for the Crab Nebula (C-rich: MacAlpine & Satterfield 2008)



Smooth models:

0.1-0.3 M⊙ of amorphous carbon dust

Clumped models:

0.4-0.6 M⊙ of amorphous carbon dust

Summary of Herschel results for core-collapse SNRs:

Cas A (330 yrs): 0.10 Msun of silicates (at least)

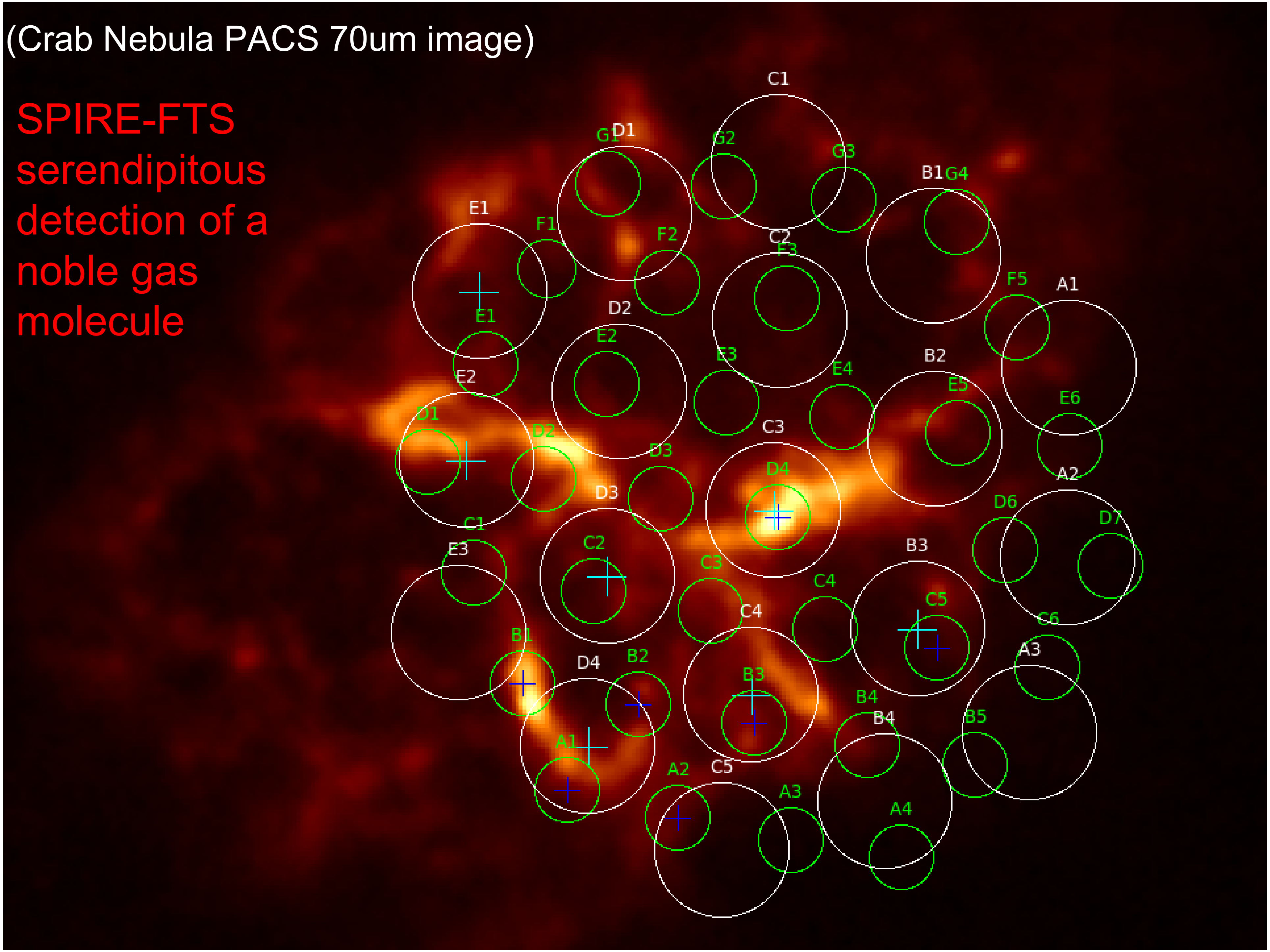
(Barlow et al. 2010)

Crab (960 yrs): 0.4-0.6 Msun of (clumped) AC carbon dust

(Owen: Session 9b)

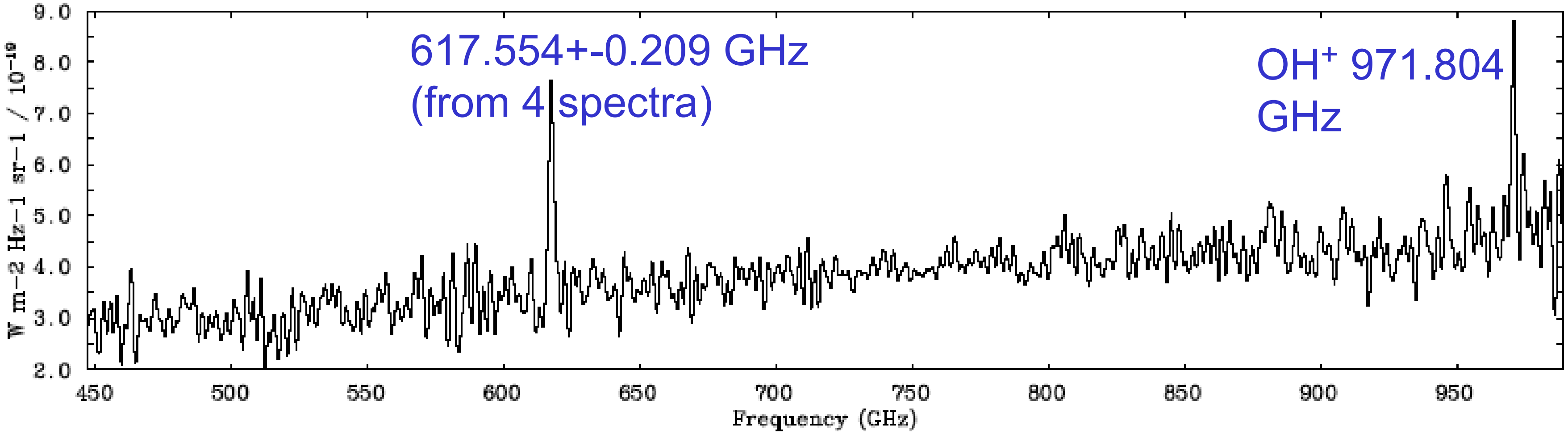
SN 1987A (25 yrs): 0.4-0.7 Msun of AC+silicates

(Matsuura et al. 2011 + Session 11b)

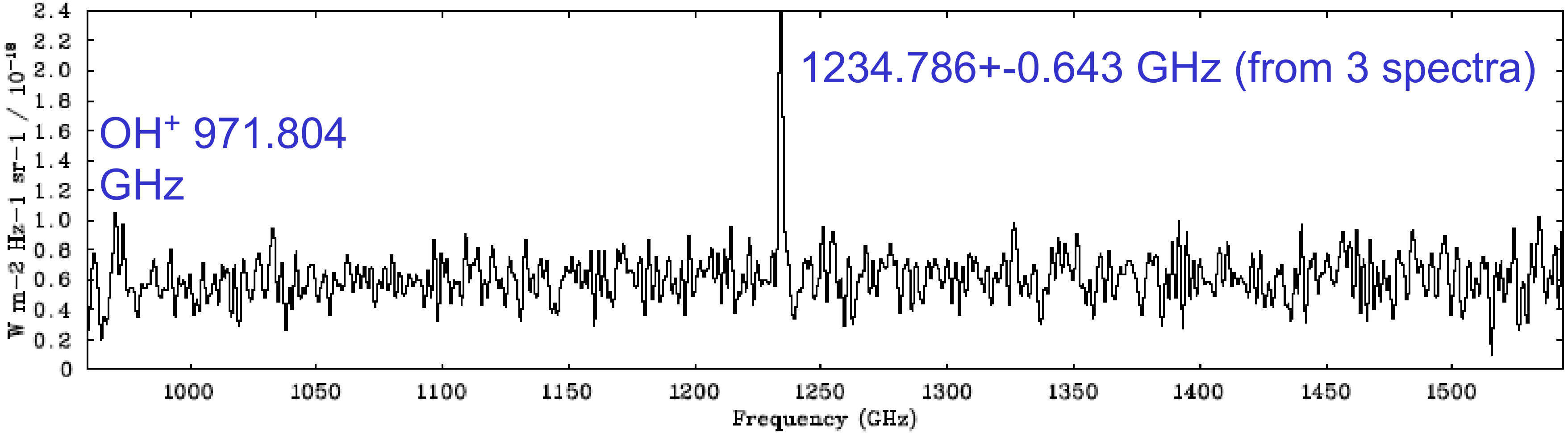

(Crab Nebula PACS 70um image)
SPIRE-FTS serendipitous detection of a noble gas molecule

SPIRE FTS spectra of the Crab Nebula

OH^+ 971.8038 GHz velocities: from -603 to +1037 km/s in multiple spectra

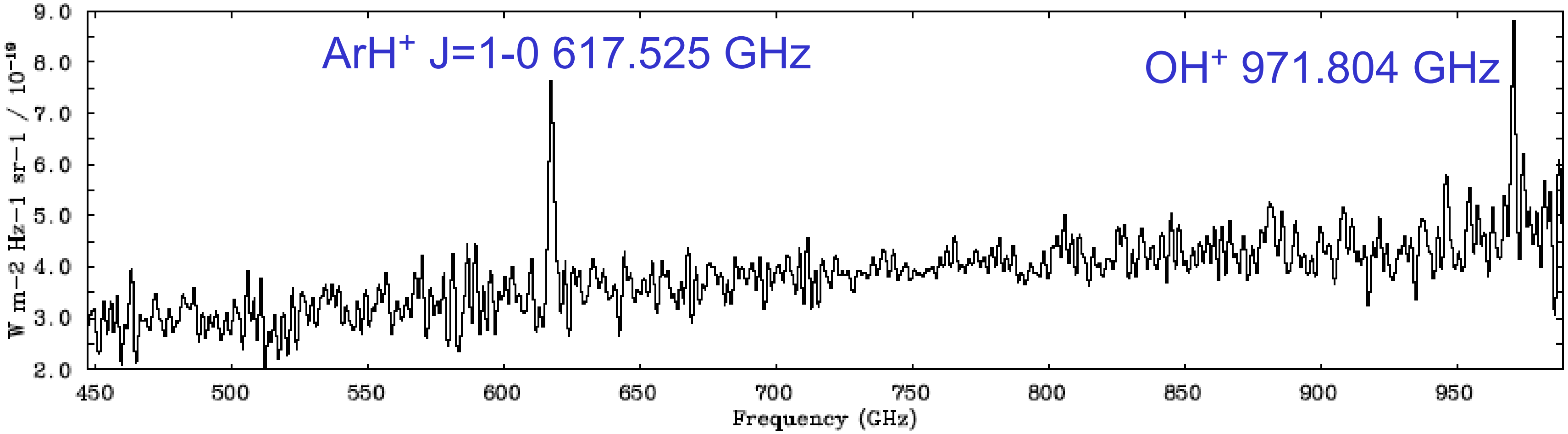


Two unidentified lines, in multiple spectra: using OH^+ velocity shifts, the frequency ratio = 1.9995+-0.0012; which suggests 2-1/1-0 rotational lines of a simple diatomic.

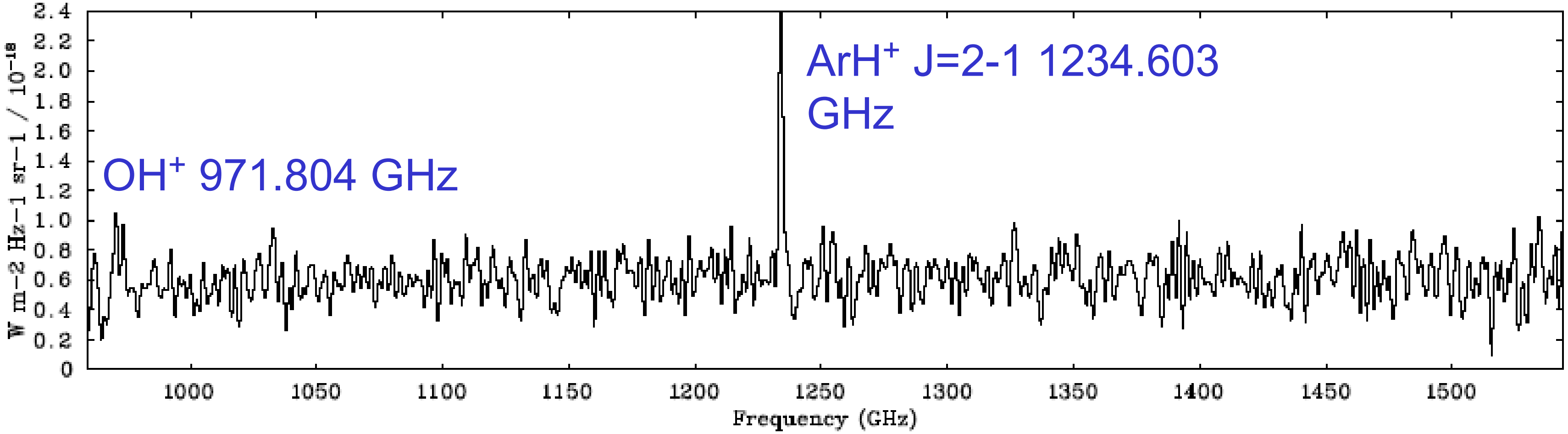


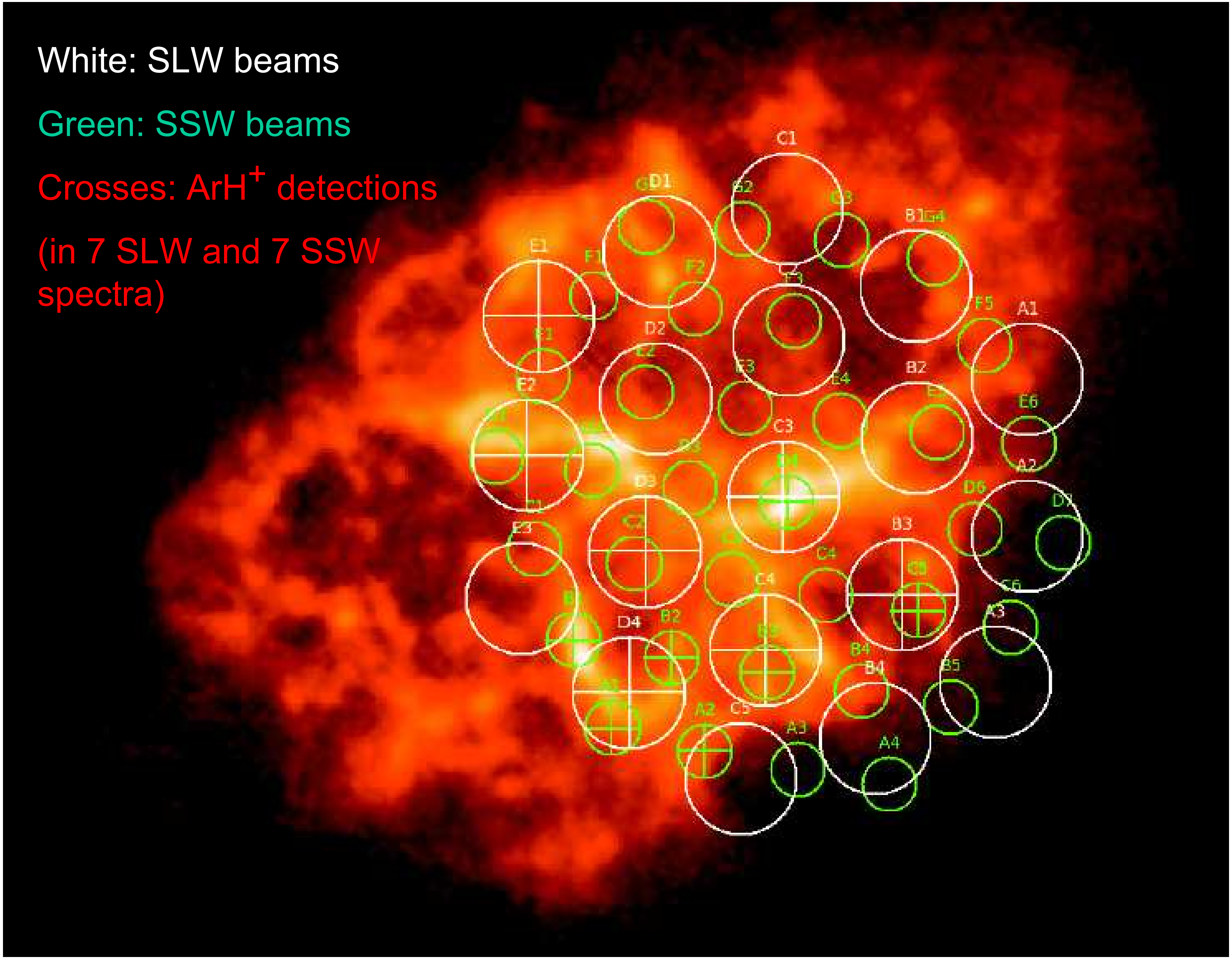
The strongest lines in the spectra: unidentified

Detection of $^{36}ArH^{+}$ (not $^{38}ArH^{+}$ or $^{40}ArH^{+}$)



First astronomical detection of a noble gas molecule



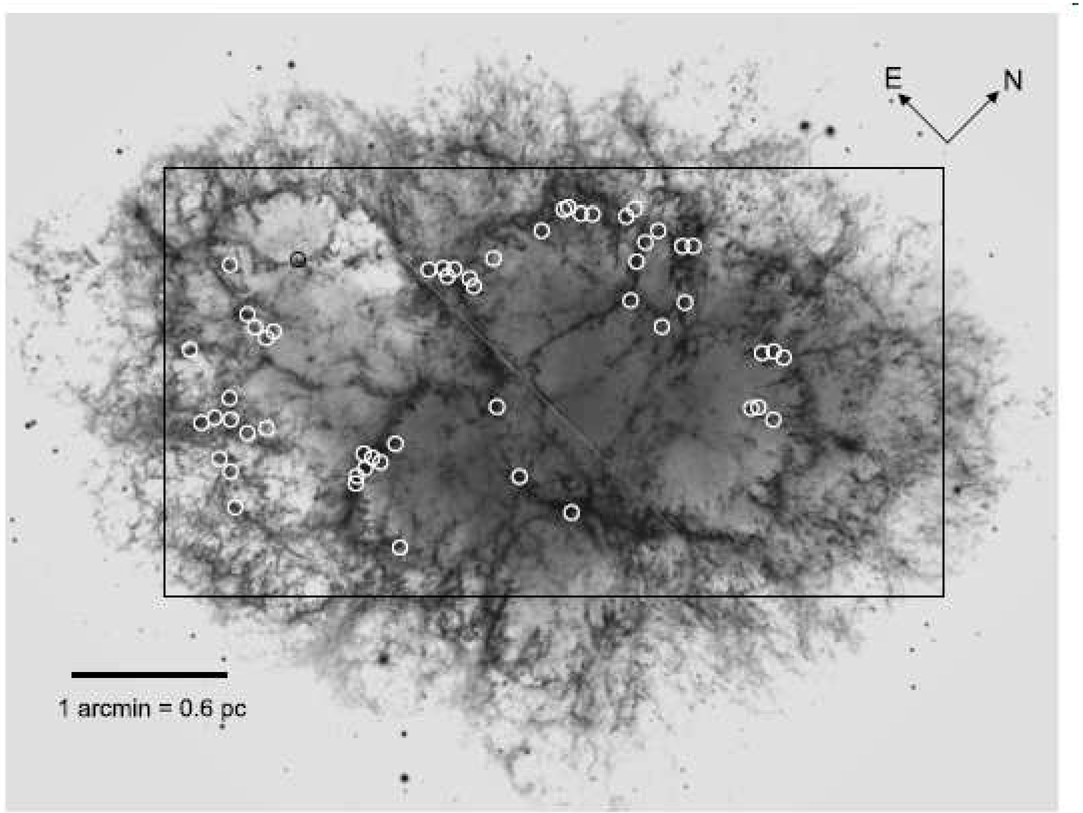

White: SLW beams
Green: SSW beams
Crosses: ArH^+ detections
(in 7 SLW and 7 SSW spectra)

Formation mechanism:

$Ar^+ + H_2 \rightarrow ArH^+ + H$ (+ 1.49 eV)

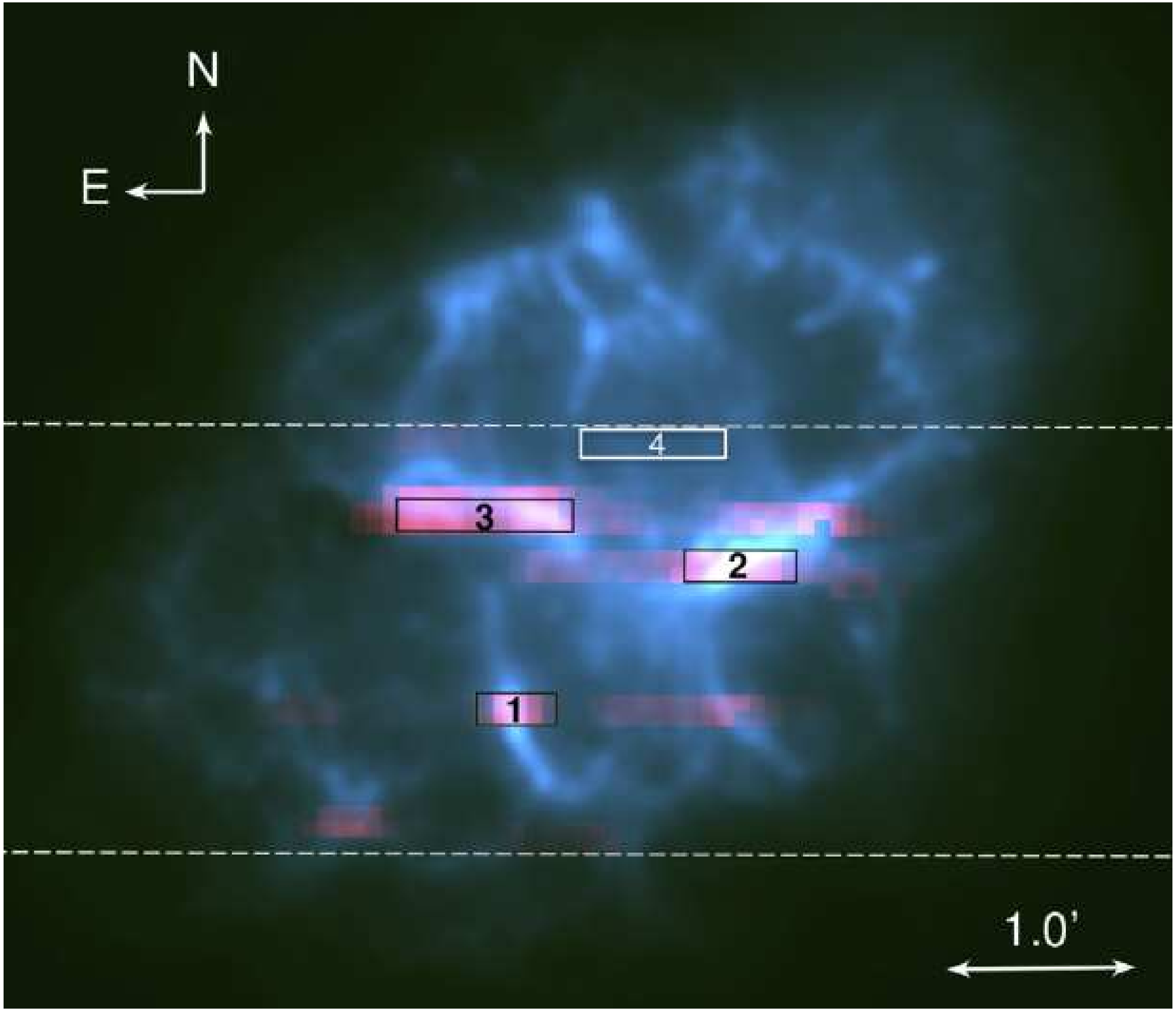
$D_o(ArH^+)$ = 3.9 eV (well-studied in the lab)

The reaction may take place in the transition regions between ionized and neutral gas. The southern filament that shows the strongest ArH^+ emission coincides with many H_2 emission knots and with a region showing enhanced ionized argon emission lines.



Loh et al. 2011: white circles show H_2 2.12um emission knots on HST optical image

Temim et al. (2012): MIPS 24um image showing Spitzer IRS positions. Region 1: strongly enhanced ionized argon lines



Argon has three stable isotopes, ^{36}Ar, ^{38}Ar and ^{40}Ar.

The $^{40}ArH^+$ and $^{38}ArH^+$ J=2-1 lines are located -3.332 GHz and –1.752 GHz away from the $^{36}ArH^+$ J=2-1 line, respectively. From our Crab FTS spectra we can set upper limits of $^{40}Ar/^{36}Ar < 5$ and $^{38}Ar/^{36}Ar < 2$ (Barlow et al. 2013, in press).

After N_2 and O_2, ^{40}Ar is the 3rd most abundant species (0.93%) in the Earth's atmosphere.

Astrophysical Quantities (4th edition, 2000) in its Cosmic Abundances table lists the atomic weight of Ar as 39.948 – Wrong! The ^{40}Ar in the Earth's atmosphere is the product of the decay of ^{40}K in rocks (half-life 1.25×10^9 yrs). But in the solar wind ^{40}Ar: ^{38}Ar: ^{36}Ar = 0.00: 1.00: 5.50 (Meshik et al. 2007).

^{36}Ar (and ^{38}Ar) are predicted to be formed by core-collapse supernovae (on the ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca chain). The Crab Nebula was the product of such a CC-SN and therefore a creation site for ^{36}Ar.

The observed $^{36}ArH^+$ J=2-1/J=1-0 flux ratios of 2.0 – 2.5 are well below the LTE limit of ~30 for T(gas) > 400K.

Ion-molecule formation and destruction rates for ArH^+ exist, but not photo-dissociation rates, nor rotational excitation rates for electron or H_2 collisions with ArH^+.

If we instead adopt known He + SiH^+ excitation rates for H_2 + ArH^+ and known e + CH^+ excitation rates for e + ArH^+, then using MADEX (Cernicharo 2010), we find that the observed 2-1/1-0 ratios require $n(H_2)$ ~ few x 10^6 cm^{-3} (which conflicts with $n(H_2)$ ~ few x 10^4 cm^{-3} found by Loh et al. (2012) from the near-IR H_2 lines), or alternatively n(e-) ~ 500 cm^{-3}, in a partially ionized transition region.

On Tuesday (Plenary A), Ewine van Dishoeck showed a broad unidentified absorption feature seen at ~617-618 GHz in the HIFI spectrum of Sgr B2. It seems plausible that the feature is due to J=0-1 617.525 GHz absorption by $^{36}ArH^+$ along the interstellar sightline.